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QUANTUM CONTROL, QUANTUM INFORMATION PROCESSING, AND QUANTUM-LIMITED METROLOGY WITH TRAPPED IONS

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We briefly discuss recent experiments on quantum information processing using trapped ions at NIST. A central theme of this work has been to increase our capabilities in terms of quantum computing protocols, but we have also applied the same concepts to improved metrology, particularly in the area of frequency standards and atomic clocks. Such work may eventually shed light on more fundamental issues, such as the quantum measurement problem.

1. Introduction

In 1995, Ignacio Cirac and Peter Zoller described how an ensemble of trapped ions could be used to implement quantum information processing (QIP).[1] Several experimental groups throughout the world have pursued this basic idea, and although a useful device still does not exist, ion-trappers are optimistic that one can eventually be built. In part, this is because the ion-trap scheme can satisfy the basic requirements for a quantum computer as outlined by DiVincenzo[2]: (1) a scalable system of well defined qubits, (2) a method to reliably initialize the quantum system, (3) long coherence times, (4) existence of universal gates, and (5) an efficient

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measurement scheme. Most of these requirements have been demonstrated, and straightforward, albeit technically difficult, paths to solving the remaining problems exist. In this paper, we summarize recent trapped-ion QIP experiments carried out at NIST, but note that similar work is currently being pursued at Aarhus, Barcelona, Garching (MPQ), Innsbruck, LANL, London (Imperial), Ontario (McMaster), Michigan, MIT, Oxford, Siegen, Sussex, Teddington (NPL), and Ulm.

We describe how the system might be scaled up by use of an array of interconnected trap zones and cite experimental implementation of algorithms that utilize the basic elements of this scheme. We then summarize efforts devoted to construction of traps by use of methods that are suitable for large-scale fabrication. We briefly discuss how QIP methods might be used in metrology, and finally suggest how QIP studies might eventually shed light on fundamental issues of decoherence.

2. QIP with multiplexed ion trap arrays

Although large numbers of ions can be cooled into regular arrays in single traps, many of the practical N-ion gates ($N \geq 2$), such as the original Cirac/Zoller two-ion gate,[1] require addressing of individual ions and single modes (or a very small number of modes) of ion motion. Individual ion addressing can be accomplished with focused laser beams as long as the ions aren't too close together (or equivalently, as long as the mode frequencies are not too high). Mode addressing is usually accomplished by spectrally isolating the mode(s) of interest (out of $3N$ possible modes). This has the consequence that when the number of trapped ions becomes large, the mode spectrum becomes so dense that spectral isolation becomes impractical. Although the group at Innsbruck has successfully implemented a number of interesting algorithms on multiple ions in single trap zones by using focused laser beams for individual qubit addressing (see their contribution to these proceedings), as the number of ions increases further, and increased gate speeds (proportional to mode frequencies) become more important, such addressing will become more difficult.

Therefore, many groups are considering a multiplexed system of trapping zones where only a small number of ions are confined in the zones that are used for implementing gates. The sharing of quantum information between zones might be accomplished by moving ion qubits between zones,[3,4] by moving an information-carrying "head" ion between zones,[5] by coupling separated ions with photons as an intermediary,[6] or by probabilistically

creating entangled pairs of separated ions via light coupling, which then act as a computational resource to be used later.[7]

2.1. *QIP in a linear ion trap array*

As a first step towards multiplexing, we have used a six-zone linear array that is an extension of the three-zone trap reported earlier.[8] Recent experiments with this device have included demonstrations of quantum teleportation,[9] quantum error correction,[10] quantum-dense coding,[11] and the quantum Fourier transform.[12]

These experiments required that entanglement between ions was preserved when the ions were located in different zones. Referring to Fig. 1, entanglement was created in zone A, and the ions were sent to zone S for separation. Electrode S is relatively narrow to facilitate separation of a single group of ions into subgroups by inserting a potential wedge between selected ions. For example, in the teleportation experiment on $^9Be^+$ ions,[9] three ions could be separated into a group of two which were delivered to zone A, with the third ion delivered to zone B. We optimized the separation to minimize the heating of the ions delivered to zone A. With a separation time of 200 μs, the ions could be separated without error. The axial center-of-mass motion of ions in zone A (frequency ~ 3 MHz) experienced a kinetic energy increase corresponding to about 1 quantum, the stretch mode had gained negligible kinetic energy, and the axial motion in zone B gained about 10 quanta. In the future, traps with much smaller internal dimensions should enable shorter separation times with negligible heating, due to the higher motional frequencies and sharper separation potential wedge features. However, with all other parameters held constant, smaller dimensions will aggravate ion heating[13] and sympathetic cooling will likely be required to maximize gate fidelity.[3,4]

Other recent experiments in these traps (that did not require multiple zones) included investigations of spontaneous emission decoherence during Raman transitions[14] and a long-lived (τ_1, $\tau_2 > 10$ s) qubit memory based on first-order magnetic field-insensitive transitions.[15]

2.2. *Future ion trap arrays*

For manipulating very large numbers of ions with high gate speeds, it appears that new types of trap construction methods, including two-dimensional layouts, will be required. Since (two-qubit) gate speed is proportional to the ions' motional frequencies, which are in turn proportional
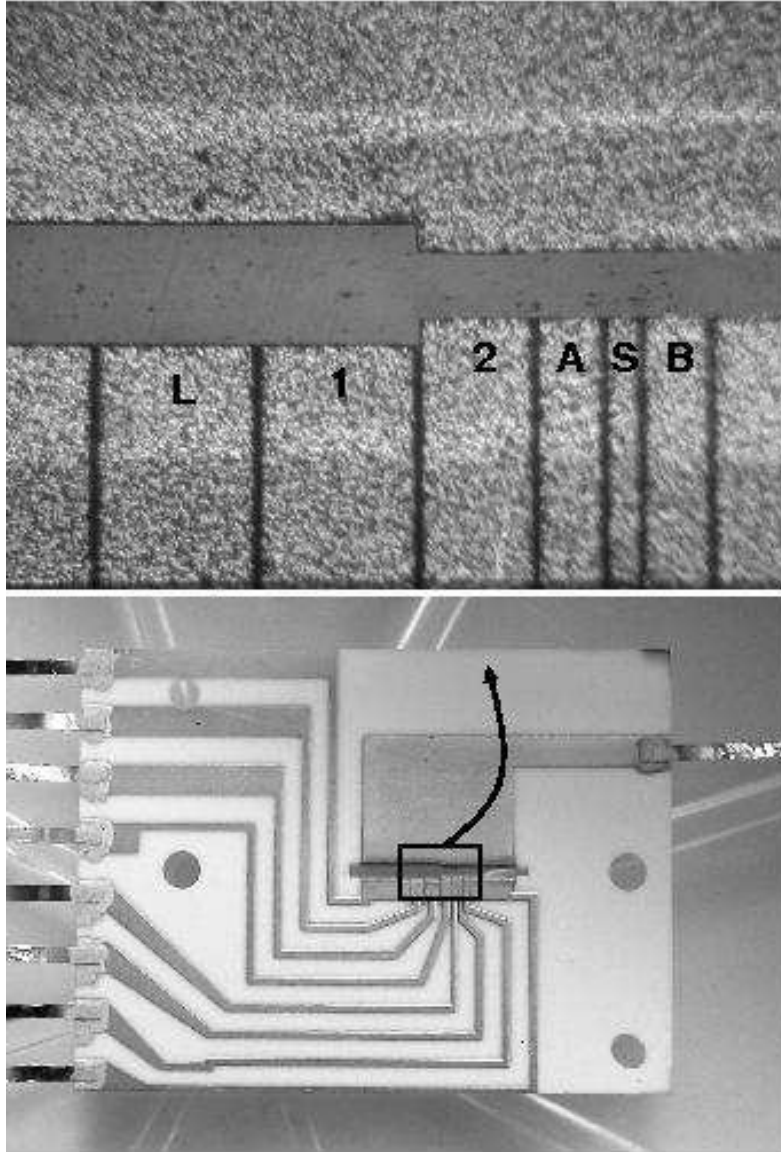
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Figure 1.   Photograph of one wafer of a six-zone linear trap array. Two of these wafers, properly spaced, comprise the trap as described in [8]. The lower part of the figure shows gold traces (approximately 3 μm thick) deposited onto an alumina substrate (lighter color). The upper figure is an expanded view of the boxed section shown below. For the wafer shown, an RF potential ($\sim$ 200 V at $\sim$ 150 MHz) is applied to the upper (continuous) electrode. "Control" potentials are applied to the eight segmented electrodes. Varying the potentials on these electrodes in a coordinated way enables ions to be moved between the six zones located above the electrodes labeled L,1,2,A,S, and B. Zone L is the "Loading" zone, whose width is relatively large to increase the capture volume for beryllium atoms (emitted from a thermal source) that are ionized (by electron impact) in this area. In most of the algorithms demonstrated using this trap, zones A and B ("Alice" and "Bob") were used to manipulate the internal states of qubits (with laser beams overlapping those zones). (Traps constructed by M. D. Barrett and J. D. Jost)

to (electrode dimensions)$^{-2}$, we would like to implement traps with dimensions smaller than those of the traps indicated in Fig. 1. Such gold coated alumina electrode structures,[8,9,16] have a size limitation from the fact that the laser-machined cuts in the wafers are limited to a width of around 20 μm.

To overcome this limitation, it should be possible to take advantage of MEMS fabrication techniques, where significantly smaller structures can be fabricated. If this is done, we must of course worry about ion motional heating, which increases as the electrodes become smaller.[13] An obvious construction material would be silicon; however, with typically available substrates, RF loss at the trap drive frequency appears to be a problem.

At NIST we constructed a single-zone two-layer trap of the type described in Ref. [8] whose electrodes were made of commercially available boron-doped silicon (Fig. 2). In this apparatus, we trapped and laser cooled ^{24}Mg$^+$ ions. Electrode features as small as 5 μm were defined by use of photolithography and industry standard silicon deep reactive ion etching (DRIE Bosch process). Structural support and spacing of the electrodes was provided by a borosilicate glass thermally matched to silicon and attached to the electrodes by anodic bonding.[17] Such an approach is applicable to the fabrication of many-zone large-scale traps including planar traps (below) since the number of processing steps does not increase with the number of zones in the array. In a different approach, the University of Michigan group has built a two-layer trap with GaAs electrodes and AlGaAs insulators[18] and observed trapping of Cd$^+$ ions.[a] A three-layer geometry[4] has been implemented for Cd$^+$ ions[16] and geometries that would optimize the separation of ions into separate groups have been studied.[19] Sandia researchers have fabricated arrays of very small (~ 1 μm) three-dimensional trap structures,[20] which also might be configured for QIP.

Borrowing from the groups pursuing magnetic waveguide traps for neutral atoms, linear traps based on electrodes confined to a surface might also be considered.[21] Such "planar" traps would be relatively easy to fabricate on a large scale and would permit on-board electronics beneath the electrode surface.[b]

In addition to finding a way to construct large-scale trap arrays, a way to multiplex laser beams must be sought. It might be possible to use miniature

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[a]C. Monroe, Univ. of Michigan, private communication
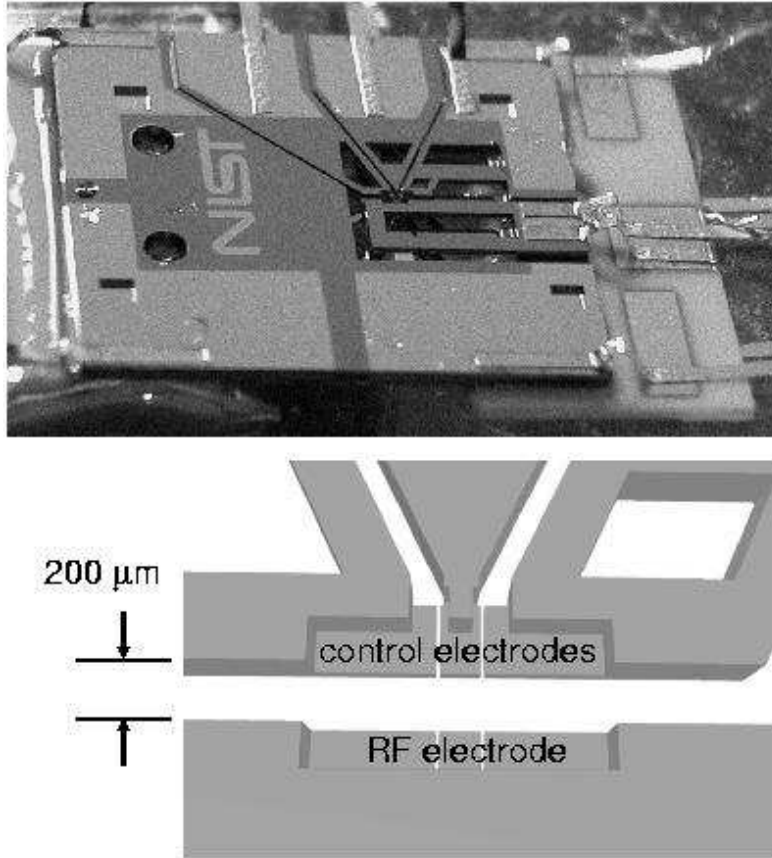[b]R. Slusher, Lucent, private communication

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Figure 2.   The photograph shows a single-zone two-layer trap of the type described in Ref. [8] The bottom part of the figure shows a schematic of the trapping region for one of the trap electrode wafers, which are fabricated from boron-doped silicon. Laser cooled ^{24}Mg$^+$ ions have been confined in this trap (constructed by J. Britton, NIST).

steerable mirrors based on MEMS technology for this purpose.[c,d] Minia-ture, large-solid-angle photon detectors (possibly without optics) located very near trapping zones may be essential for highly parallel detection as required in error correction.

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[c]O. Blum Spahn, Sandia National Labs, private communication.

[d]J. Kim, Duke University, private communication.

3. QIP applied to metrology

In the Time and Frequency Division of NIST, we have been interested in applying the methods of QIP to metrology, in particular, to improve the signal-to-noise ratio in spectroscopy and atomic clocks. For this purpose, we take advantage of entanglement. The improvement obtained from "spin-squeezed" states,[22,23,24] where the operator of the effective mean spin vector is measured, has been demonstrated for two ions.[25] We have also demonstrated the gain in signal-to-noise ratio with certain states in combination with other operators such as the variance and parity.[26,25] More recently, we have extended a two-ion phase gate[27] to implement a form of Ramsey spectroscopy where each of the two conventional Ramsey $\pi/2$ pulses are replaced with a rotation and one-step phase gate.[28] Starting with all ions in the state $|\downarrow\rangle$, the first modified "$\pi/2$" pulse generates a generalized GHZ state[29] or "Schrödinger-cat" state of the form $\frac{1}{\sqrt{2}}[|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N + e^{i\beta}|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N]$. During the Ramsey free-precession interval T, the relative phase of the two components of the wavefunction $\beta = N(\omega_0 - \omega)T$, where ω is the frequency of the probe oscillator and ω_0 is the resonance transition frequency, advances N times faster than that of a single atom. This is the main reason for the increase in spectroscopic resolution. After application of the two modified Ramsey pulses, the equivalent net spin vector is measured in the $|\downarrow\rangle$, $|\uparrow\rangle$ basis. In ideal circumstances, all ions are measured to be in either all $|\uparrow\rangle$ states with probability $P_\uparrow = \frac{1}{2}[1 + \cos N(\omega_0 - \omega)T]$ or all $|\downarrow\rangle$ states with probability $P_\downarrow = 1 - P_\uparrow$, cases that are relatively easy to distinguish. Although the fringes occur N times faster, the gain in signal-to-noise ratio is limited to $\sqrt{N}$ compared to the case of N unentangled particles, because the N unentangled particles yield a signal from N separate systems, where the "projection" noise[30] averages down as $N^{-1/2}$. Although the experimentally observed gain was limited to less than $\sqrt{N}$, we were able to demonstrate a signal-to-noise ratio better than could be obtained in a perfect experiment on unentangled ions, first on three ions[28] and more recently on up to six entangled ions.[31]

QIP might also be used to improve detection. In one application relevant for frequency standards, it was shown that transitions in a "clock" ion can be detected in a simultaneously-trapped "logic" ion by mapping the internal state of the clock ion onto the logic ion (with elementary quantum logic operations) where it is easily detected.[32] In a more general context, detection sensitivity of quantum systems can be improved in certain situations by use of elementary quantum logic operations on the system to be

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measured, in conjunction with ancilla particles that are also measured.[11]

4. QIP and the "measurement problem"

By the measurement problem, we mean the difficulty that arises because we live in a world that predicts definite outcomes (e.g., bits in our PCs are either 0 or 1) whereas quantum mechanics alone, in general leaves the world in superposition states. In addition to the simple collapse postulate, many attempts have been made to resolve the problem with ideas that include concepts such as "many worlds," decoherence theory, an as-of-yet unseen collapse mechanism, or simply that the theory of quantum mechanics is only a computational tool that allows prediction of classical outcomes (for a recent review, see for example the paper by Leggett[33]).

Given the unresolved state of affairs on the measurement problem, it seems interesting to press the issue experimentally - that is, can we realize larger and larger entangled superposition states that begin to approach our more macroscopic world where such states aren't observed? The paper by Leggett suggests one measure for approaching the classical world in which the number of elementary particles involved in a superposition state is of primary importance.[33] At this stage, since we really don't know what the important parameters are, we might cook up alternative measures that play more to the strengths of atomic physics and quantum optics. With atomic ions, we can emphasize the aspects of entanglement and duration. For example, we might take as a figure of merit the product of the number of particles in a GHZ state (since its phase sensitivity is N-fold larger than that of a single particle) times the duration of the state. A start in this direction is that a six particle approximation to a GHZ state was observed to last longer than approximately 50 μs.[31] Note also that superpositions of the (phase-insensitive) Bell states $\Psi_\pm = \frac{1}{\sqrt{2}}(|\downarrow\rangle_1 |\uparrow\rangle_2 \pm |\uparrow\rangle_1 |\downarrow\rangle_2)$ have been observed to last for durations exceeding 5 s in ^{9}Be$^+$ ions[15] and even longer for Ca$^+$ ions (see the paper by the Innsbruck group in these proceedings). Whatever your favorite measure is, it seems likely that as the quest to make a large-scale QIP machine progresses, states that look more and more like Schrödinger's cat will be produced - or not, if some fundamental source of decoherence is discovered!

Acknowledgments

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